On WIMPs and chimeras

DAVID G. CERDEÑO
IPPP, Department of Physics,
Durham University

Durham University

MULTIDARK
Multimessenger Approach for Dark Matter Detection

WARNING
Biased and Incomplete

On WIMPs and chimeras

DAVID G. CERDEÑO
IPPP, Department of Physics,
Durham University

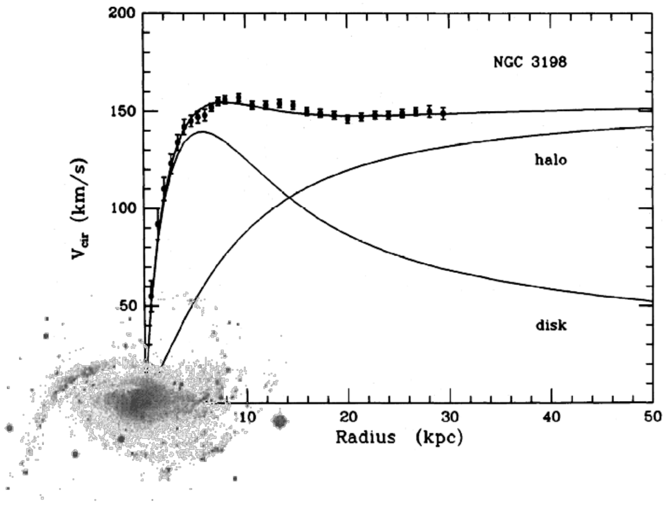
IP3 Durham University

MULTIDARK
Multimessenger Approach for Dark Matter Detection

Dark Matter is a necessary (and abundant) ingredient in the Universe

Galaxies

- Rotation curves of spiral galaxies
- Gas temperature in elliptical galaxies



It is one of the clearest hints of Physics Beyond the SM

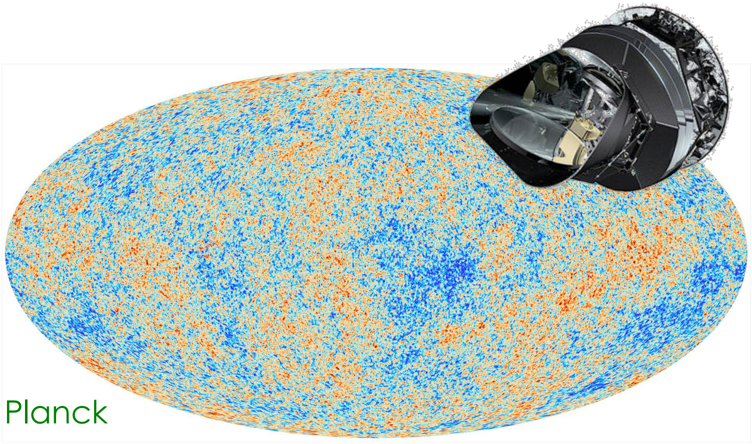
Clusters of galaxies

- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision
- Filaments between galaxy clusters

Cosmological scales

Anisotropies in the Cosmic Microwave Background

$$\Omega_{CDM}\, h^2 = 0.1196 \pm 0.003$$



Planck

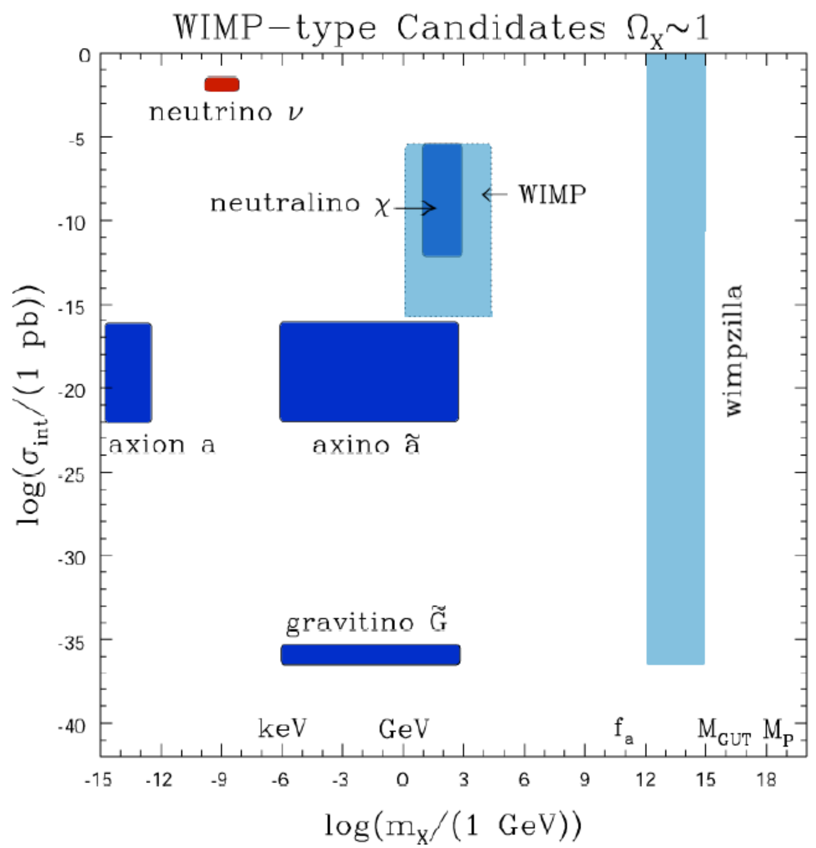
We don't know yet what DM is... but we do know many of its properties

Good candidates for Dark Matter have to fulfil the following conditions

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by current searches
- No conflicts with BBN or stellar evolution

Many candidates in Particle Physics

- Axions and ALPs
- **Weakly Interacting Massive Particles (WIMPs)**
- Self-interacting DM
- SuperWIMPs and Decaying DM
- Asymmetric DM
- SIMPs, CHAMPs, ETCs...



... they have very different properties

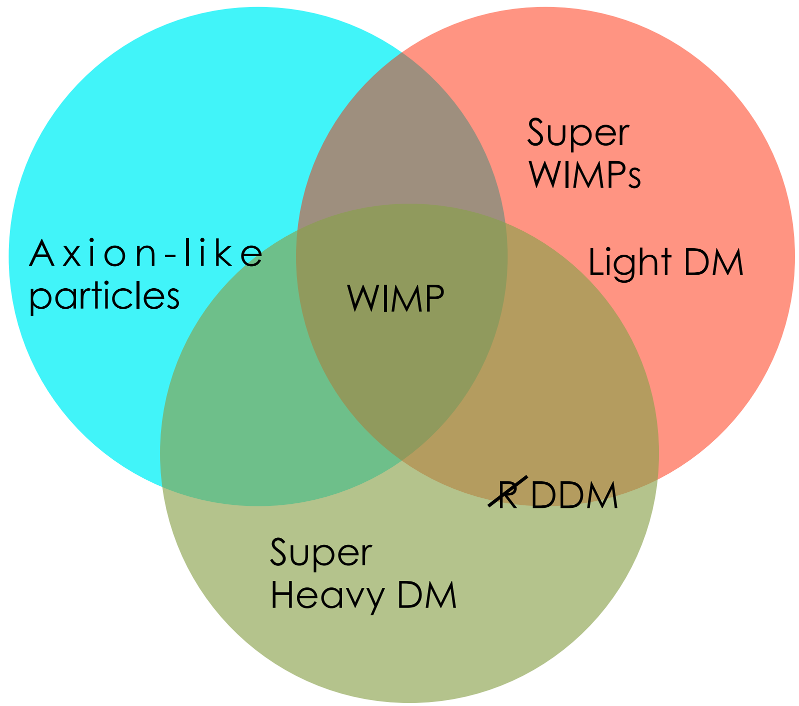
Dark Matter can be searched for in different ways...

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

DAMA/LIBRA
SuperCDMS
Edelweiss
XENON
LUX
CRESST
CoGeNT
DarkSide
KIMS
PICO
SIMPLE
ANAIS
XMASS
...



Indirect Detection

(DM annihilation)

PAMELA	ANTARES
Fermi	IceCube
MAGIC	CTA
AMS	HESS

... probing different aspects of the DM interactions with ordinary matter

Accelerator Searches (DM production) LHC (ILC)

Direct Detection

(DM-nuclei scattering)

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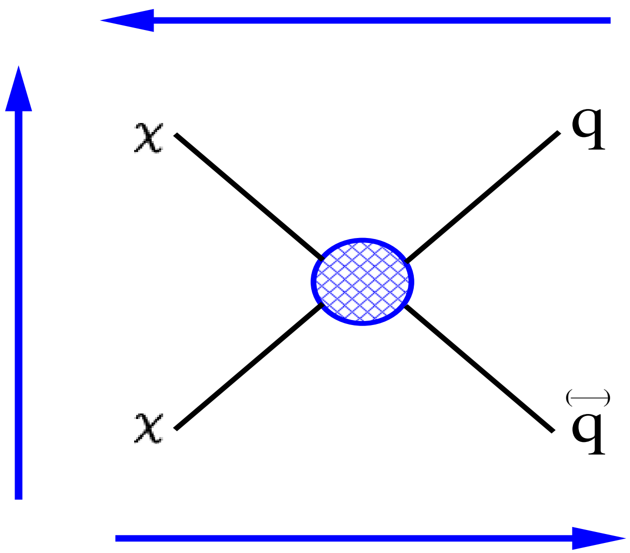


Constraints in one sector affect observations in the other two.

"Redundant" detection can be used to extract DM properties.

COMPLEMENTARITY of DM searches

Indirect Detection

(DM annihilation)

PAMELA
Fermi
MAGIC
AMS

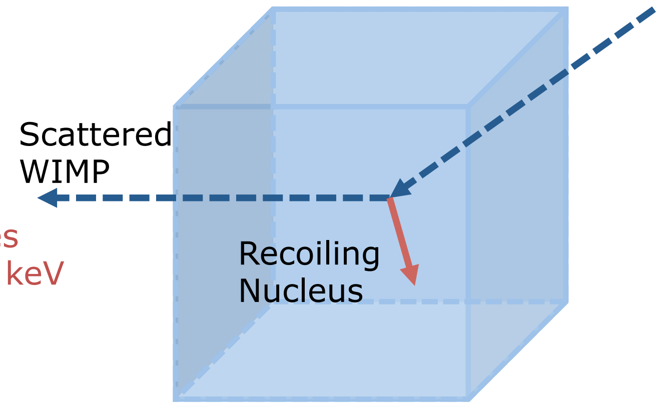
ANTARES
IceCube
CTA
HESS

Direct DM detection, where do we stand?

WIMP scattering with nuclei can be measured through

- Ionization
- Scintillation
- Phonons
- Bubble nucleation

For a 100 GeV WIMP, this implies recoil energies of order $E_R \sim$ 10 keV



Detection rate

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v\, f(v) \boxed{\frac{d\sigma_{WN}}{dE_R}(v, E_R)}\, dv$$

Experimental setup

Target material (sensitiveness to spin-dependent and –independent couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section (of WIMPs with quarks)

Nuclear uncertainties

WIMP-nucleus cross section traditionally separated in two components

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

Spin-independent contribution: scalar (or vector) coupling of WIMPs with quarks

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q + \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

Total cross section with Nucleus scales as A^2

Present for all nuclei (favours heavy targets) and WIMPs

Spin-dependent contribution: WIMPs couple to the quark axial current

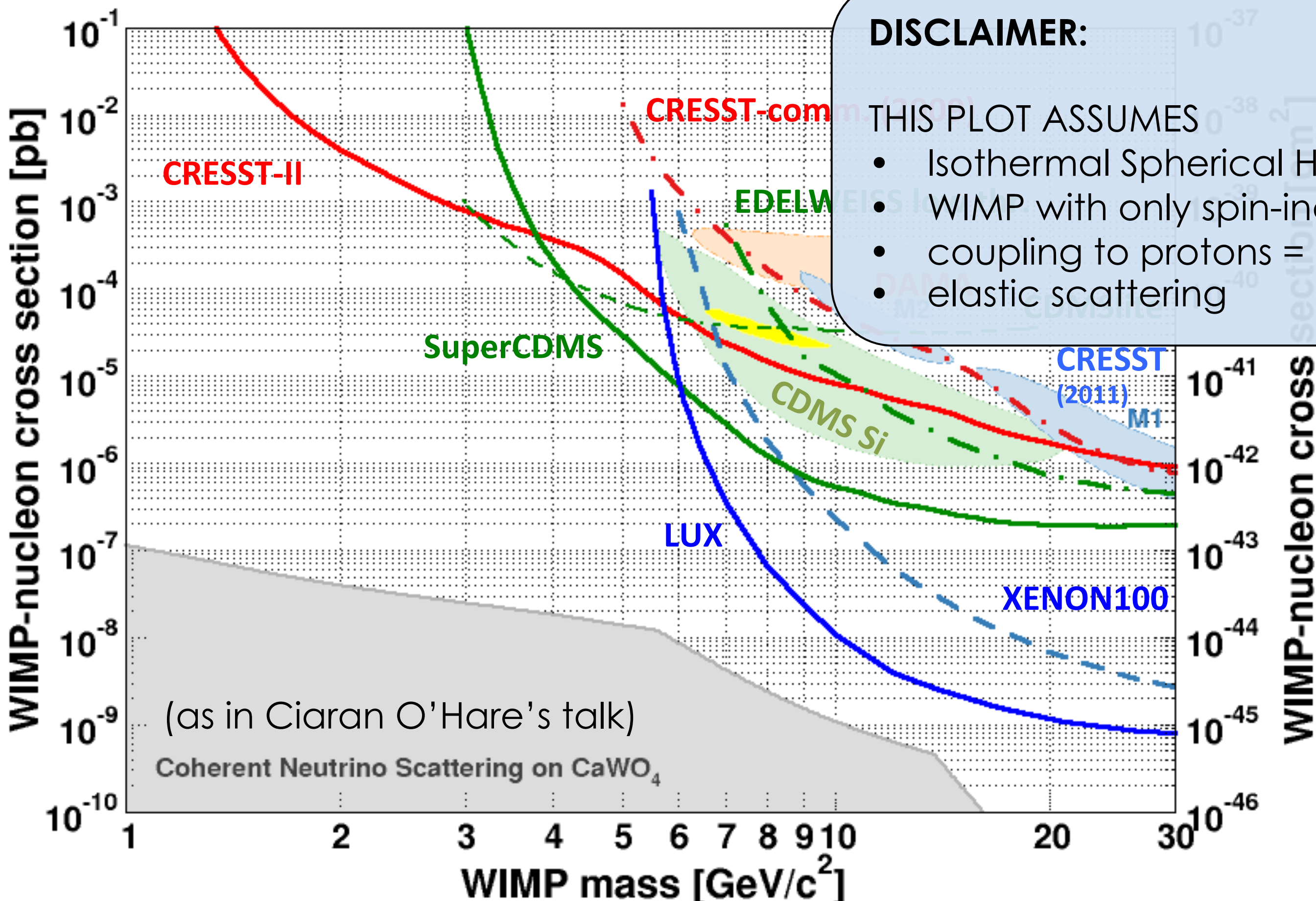
$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

Total cross section with Nucleus scales as J/(J+1)

Only present for nuclei with J≠ 0 and WIMPs with spin

Upper bounds on the SI cross section

XENON10, XENON100, LUX (Xe), CDMSlite, SuperCDMS, Edelweiss (Ge), COUPP (CF_3I), and CRESST ($CaWO_4$) have not observed any DM signal, which constrains the scattering cross section



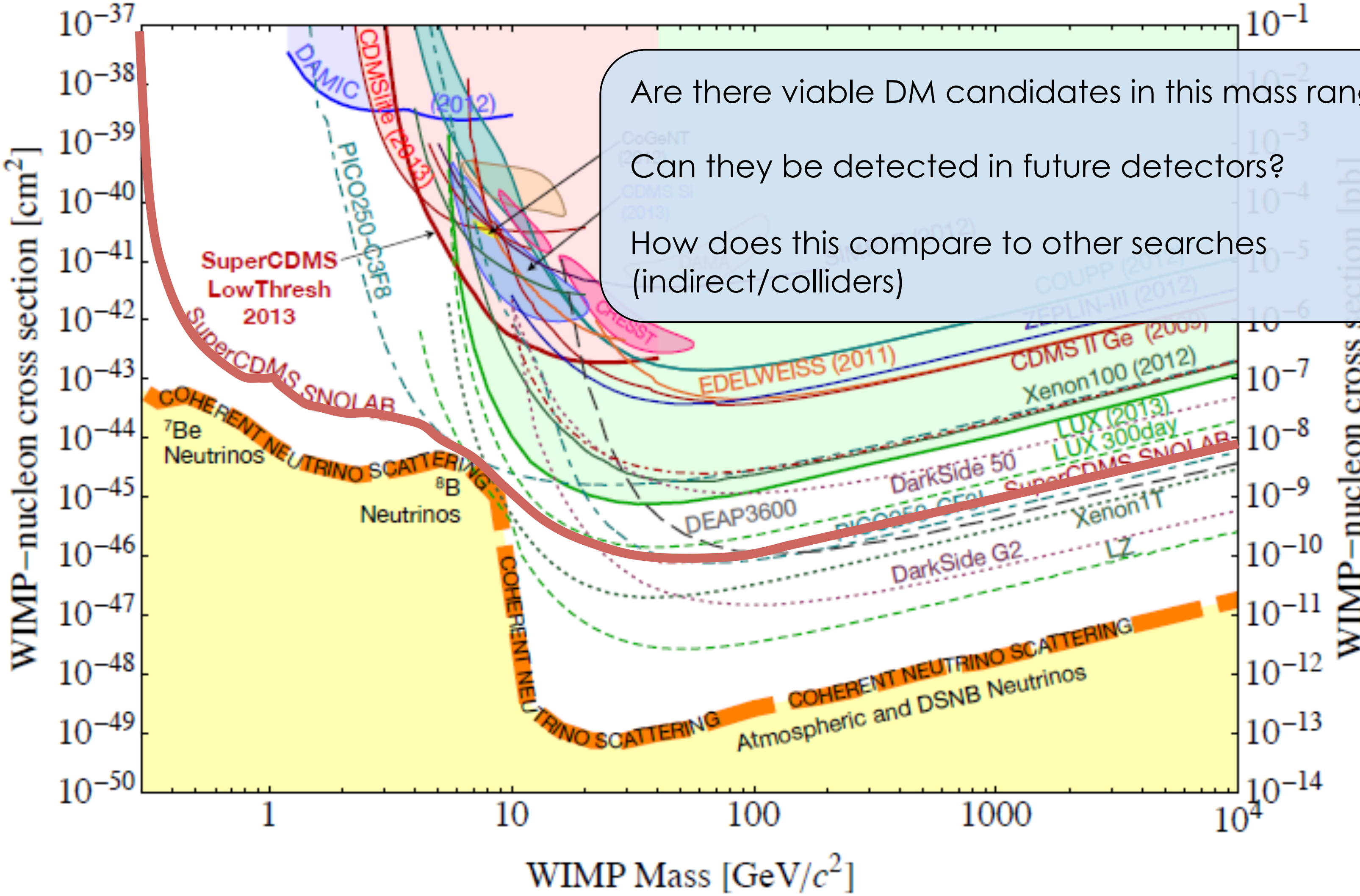
DISCLAIMER:

THIS PLOT ASSUMES

- Isothermal Spherical Halo
- WIMP with only spin-independent interaction
- coupling to protons = coupling to neutrons
- elastic scattering

Plot by Raimund Strauss

2nd Generation experiments will extend the sensitivity by over an order of magnitude.
SuperCDMS @ SNOLAB will have an excellent coverage of the light mass window.



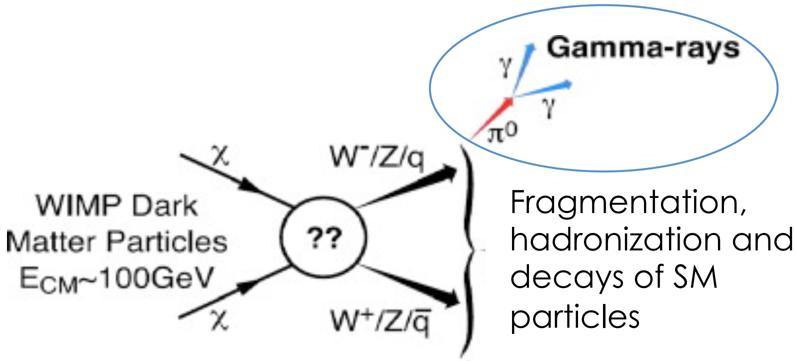
Are there viable DM candidates in this mass range?

Can they be detected in future detectors?

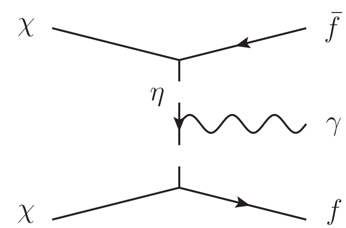
How does this compare to other searches (indirect/colliders)

Gamma rays from DM annihilation

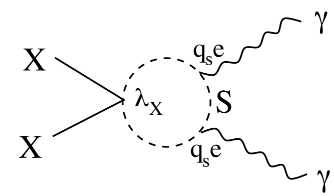
Continuum (secondary photons)



Direct gamma emission (features, lines)



Internal bremsstrahlung



Loop processes

$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right) = \sum_i \frac{dN^i_\gamma}{dE_\gamma} \boxed{\langle\sigma_i v\rangle} \frac{1}{8\pi m^2_{DM}} \boxed{\int d\Omega \int_{l.o.s.} \rho^2(r(l,\Psi))\; dl}$$

Theoretical input

DM annihilation cross section IN THE HALO

$$\langle\sigma v\rangle \approx a + bv^2$$

$$v^2_{Decoupling} \approx 1/20$$

$$v^2_{halo} \approx 10^{-7}$$

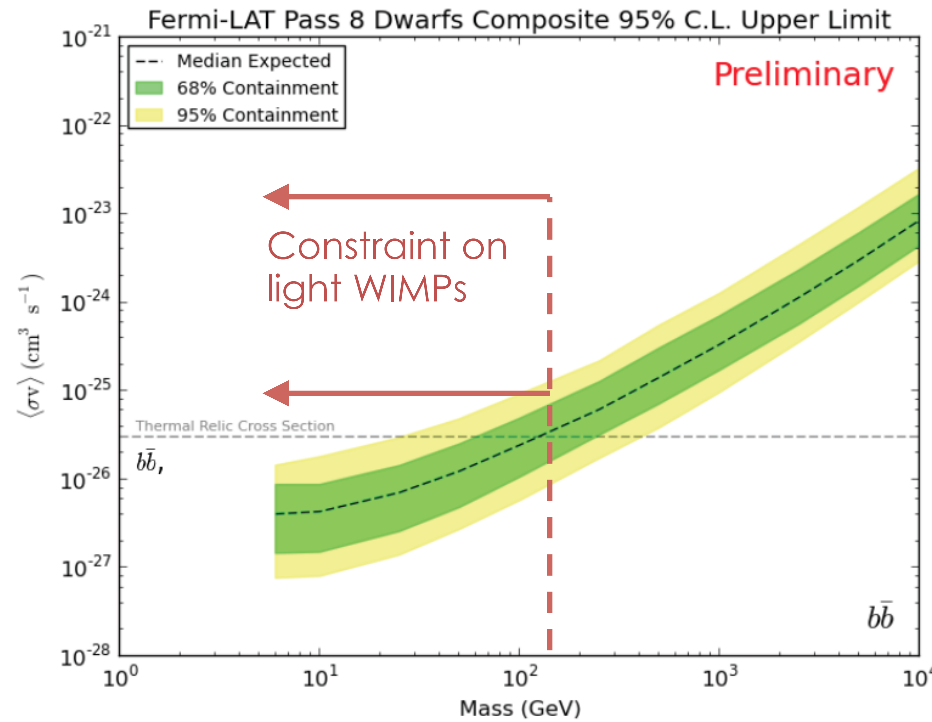
Astrophysical input

DM Density profile

Region of observation (backgrounds)

Fermi-LAT can provide constraints for light WIMPs

Fermi-LAT '14

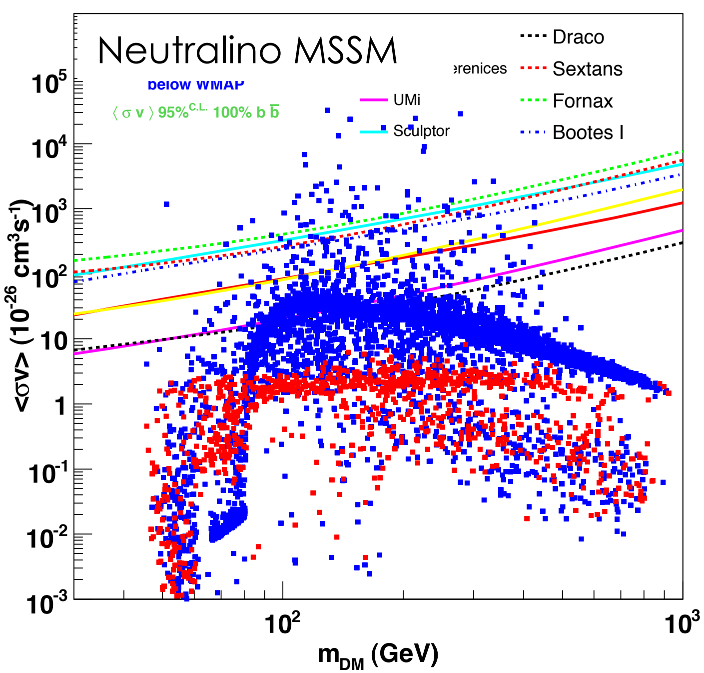


Fermi-LAT observation of Dwarf Spheroidals

Fermi-LAT '11

Thermal cross-section excluded for some channels (bb and $\tau\tau$)

m>100 GeV for the bb channel

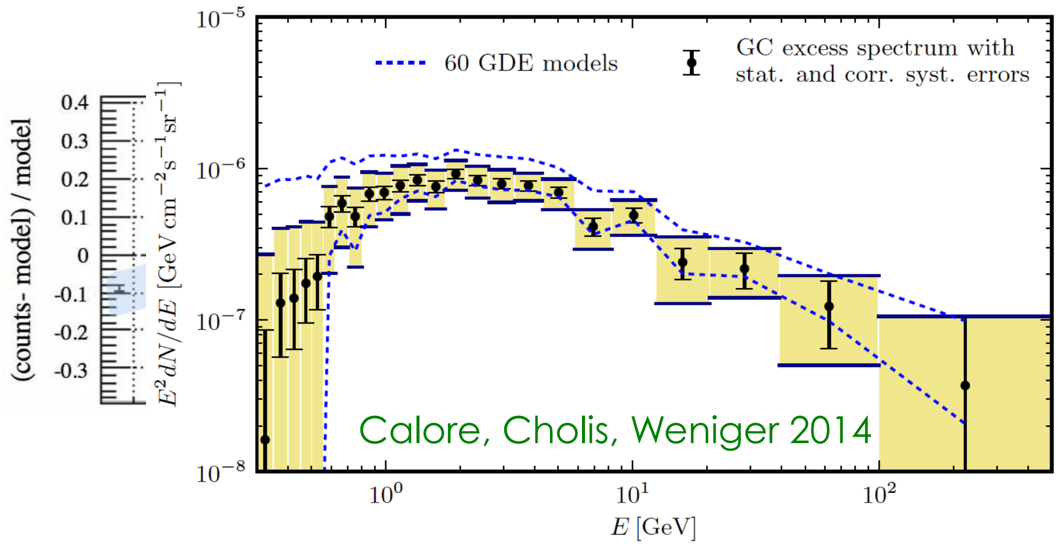


Abdo et al. 1001.4531

"Thermal" DM might have a smaller <sv> in the halo

Coannihilation effects,
velocity-dependent cross-section
resonances

Excess at low energies in Fermi-LAT data from the GC



Compatible with the annihilation of a light WIMP ~10-50 GeV

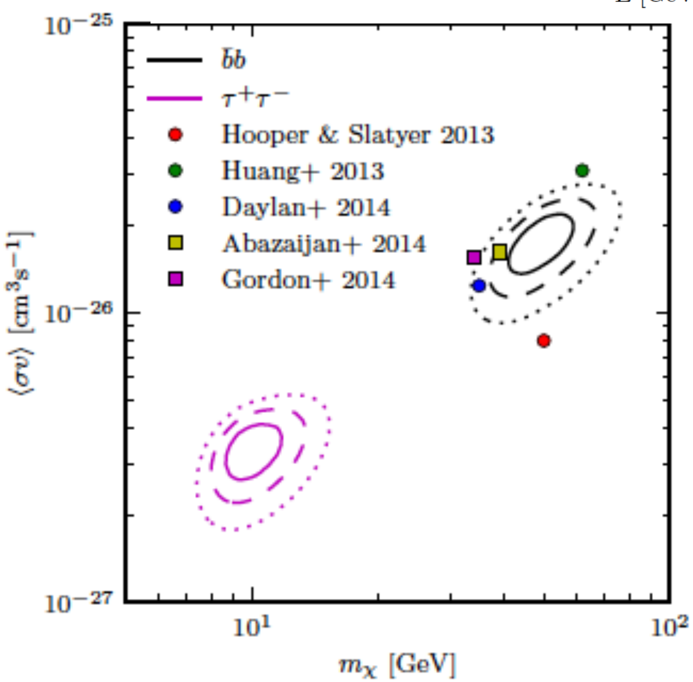
Hooper, Goodenough 2010
Hooper, Linden 2011
Hooper, Linden 2012-2014

or cosmic ray outbursts

Cholis et al. 1506.05119

or millisecond pulsars

Bartels et al. 1506.05104



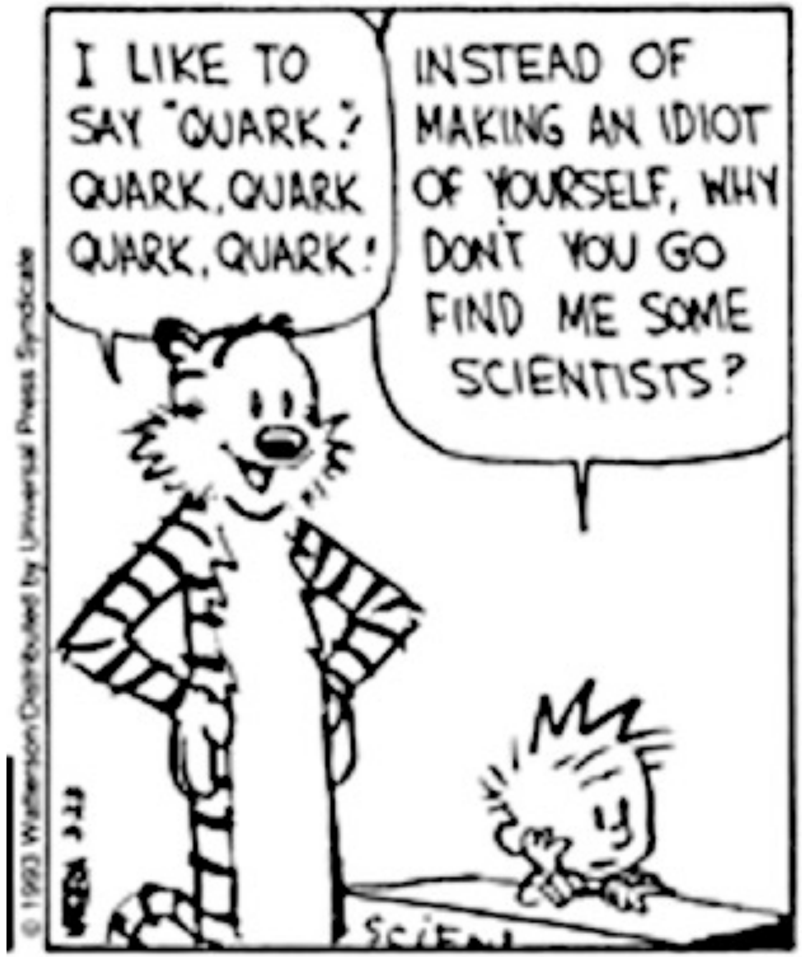
Fits normally done for pure annihilation channels

Compatible with WIMP DM

$$m_{DM} \sim 20 - 100 \text{ GeV}$$

$$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$$

What have theorists done in the meanwhile?



Taxonomy vs. Taxidermy

Taxonomy (Theory–biased)

Construct a bestiary of “well motivated models”

Predictions are tested with experimental results

- “Standard” WIMPs
  - Supersymmetry (neutralinos, **sneutrinos**)
  - Kaluza-Klein DM
  - Inert doublet model
  - …

- Asymmetric DM
- Inelastic DM
- Decaying DM (e.g., gravitinos)
- Axions
- Self-interacting DM
- …

Particle Physics models for dark matter

Well motivated DM models in theories beyond the Standard Model (e.g., Supersymmetry)

Minimal SUSY extension

Squarks	$\tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$, $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$, $\tilde{b}_{R,L}$
Sleptons	$\tilde{e}_{R,L}$, $\tilde{\nu}_e$ $\tilde{\mu}_{R,L}$, $\tilde{\nu}_\mu$ $\tilde{\tau}_{R,L}$, $\tilde{\nu}_\tau$
Neutralinos	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
Charginos	$\tilde{W}^\pm$, $\tilde{H}^\pm_{1,2}$
Gluino	$\tilde{g}$

Neutralino

Good annihilation cross section. it is a WIMP

Goldberg '83

Ellis, Hagelin, Nanopoulos, Olive, Srednicki '83

Krauss '83

Sneutrino

Viable candidates in scenarios with Right-Handed sneutrinos

Cerdeño, Muñoz, Seto 08

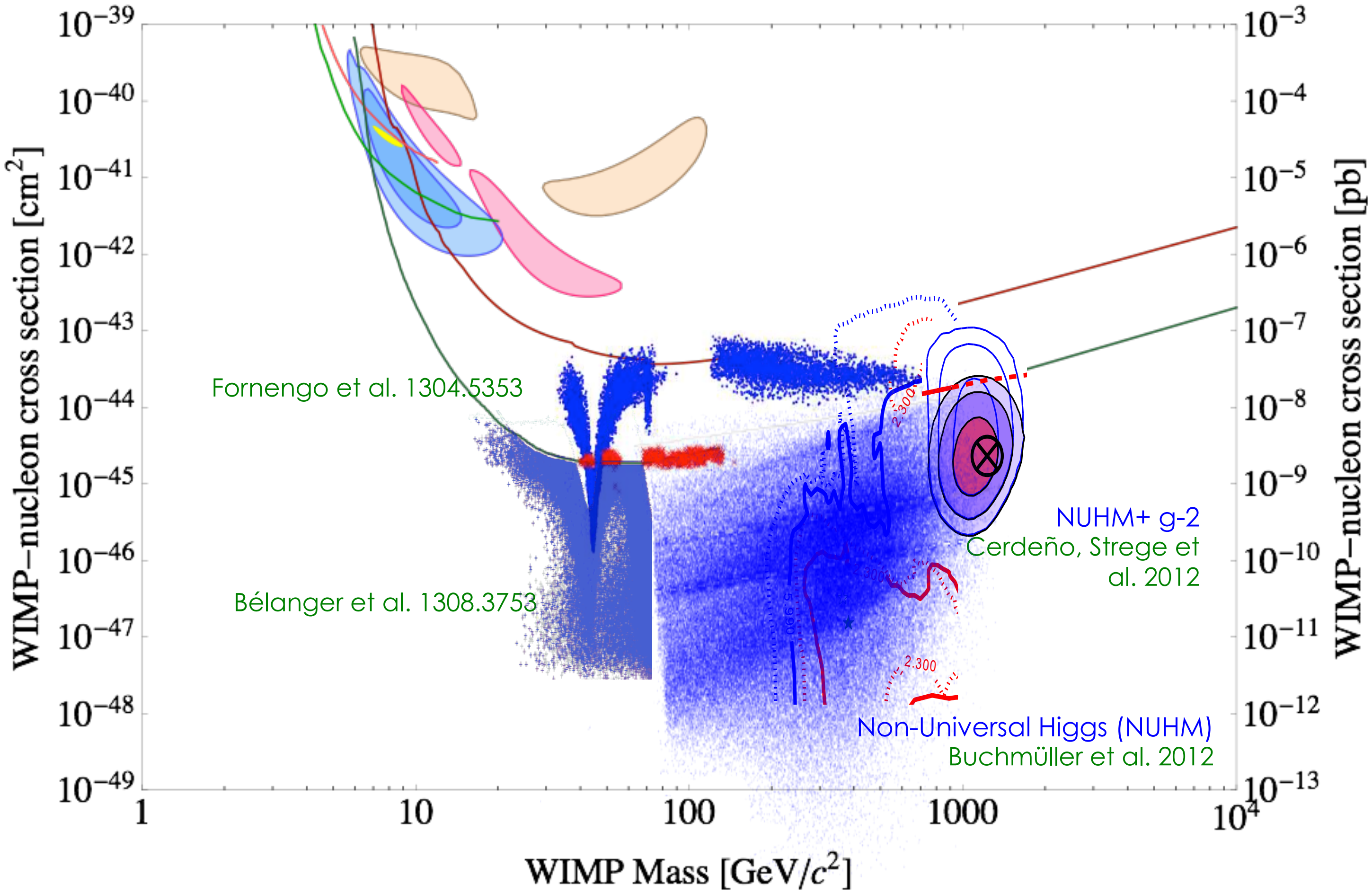
Arina, Fornengo 08

Gravitino (Superpartner of the graviton)

Axino (Superpartner of the axion)

Extra-weakly interacting massive particles

Neutralino in the MSSM



The predictions for its scattering cross section still span many orders of magnitude (excellent motivation for more sensitive detectors)

Right-handed sneutrino in the NMSSM

DGC, Muñoz, Seto 2007 , DGC, Seto 2009

- Addition of TWO new superfields, ***S***, ***N***, singlets under the SM gauge group

$$\mathrm{NMSSM} \quad = \quad \mathrm{MSSM} + \hat{S} \left\{ \begin{array}{l} 2 \text{ extra Higgs (CP}-\text{even, CP}-\text{odd)} \\ 1 \text{ additional Neutralino} \end{array} \right.$$

$$+ N \left\{ \begin{array}{l} 1 \text{ additional (right-handed) Neutrino} \\ \text{and sneutrino} \end{array} \right.$$

- New terms in the superpotential

$$W = Y_u\, H_2\, Q\, u + Y_d\, H_1\, Q\, d + Y_e\, H_1\, L\, e - \lambda\, S\, H_1 H_2 + \frac{1}{3}\kappa S^3$$

$$W \quad = \quad W_{\mathrm{NMSSM}} + \lambda_N S N N + y_N L \cdot H_2 N$$

- After Radiative Electroweak Symmetry-Breaking

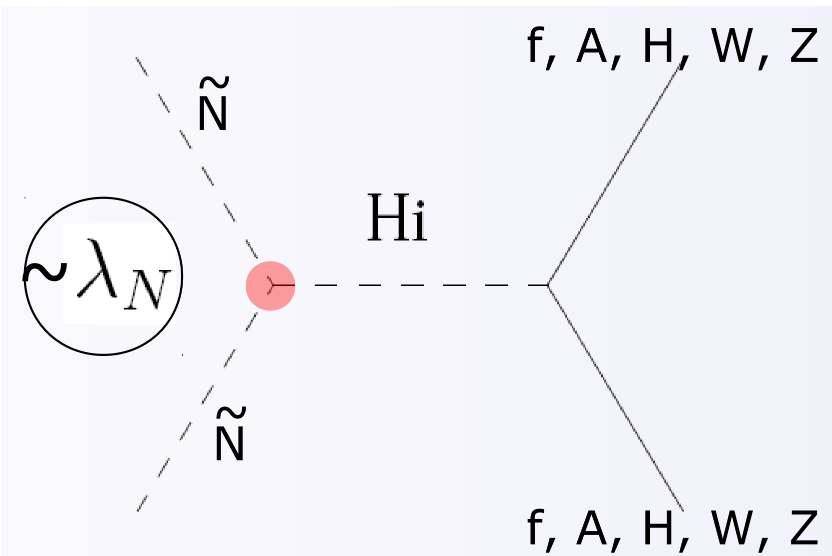
$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s \qquad \left\{ \begin{array}{l} \mu\, H_1\, H_2 \\ \\ m_N N\, N \end{array} \right.$$

EW-scale Higgsino-mass parameter & Majorana neutrino mass

EW-scale see-saw mechanism implies very small yukawa couplings

$$m_{\nu_L} = \frac{y_N^2 v_2^2}{M_N} \longrightarrow y_N = \mathcal{O}(10^{-6})$$

Since this determines the LR mixing of the neutrino/sneutrino sector one is left with pure Right and Left fields



Correct relic density → λ_N~0.1 (it is a WIMP)

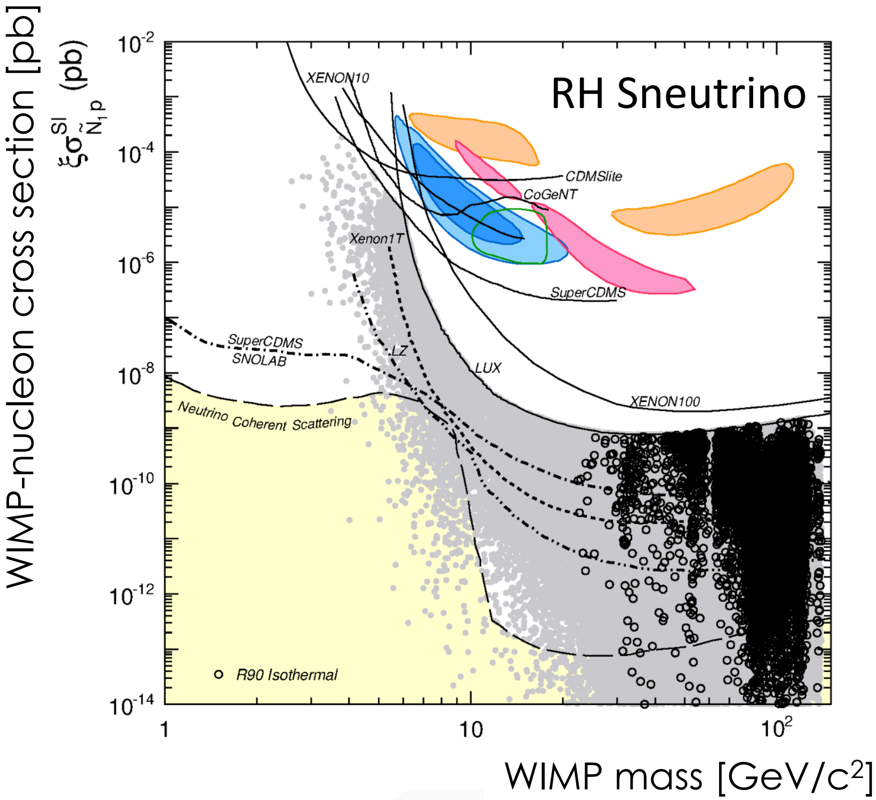
DGC, Muñoz, Seto 0807.3029
DGC, Seto 0903.4677

Other solution for sneutrino dark matter consists in considering LR-sneutrinos

Arina, Fornengo 0709.4477

Right-handed sneutrino in the NMSSM

DGC, Muñoz, Seto 2007 , DGC, Seto 2009



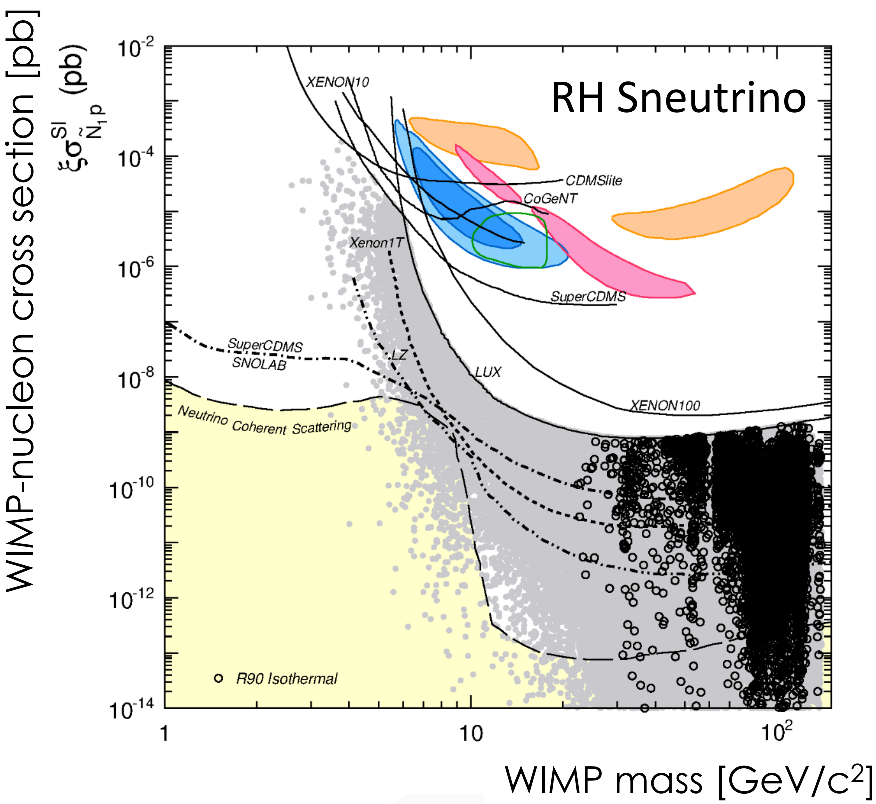
DGC, Peiró, Robles JCAP 08 (2014) 005
DGC, Peiró Robles – in progress

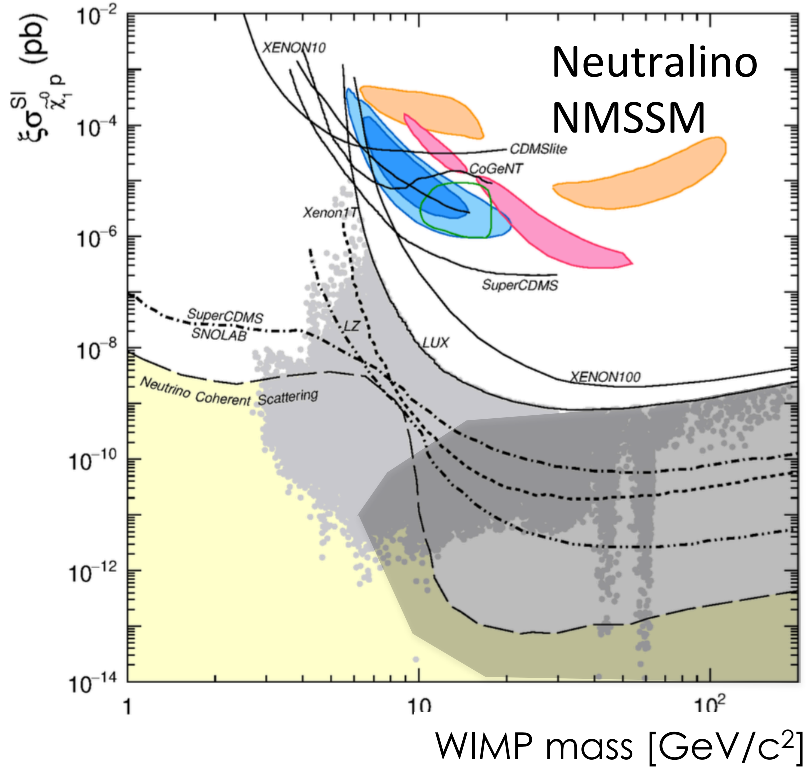
- Sneutrinos as light as ~5 GeV can be found, which satisfy all constraints
- Scattering cross section within the range of G2 experiments
- Black dots can also be explored through gamma ray lines

Excellent motivation for direct searches at low masses

Right-handed sneutrino in the NMSSM

DGC, Muñoz, Seto 2007 , DGC, Seto 2009





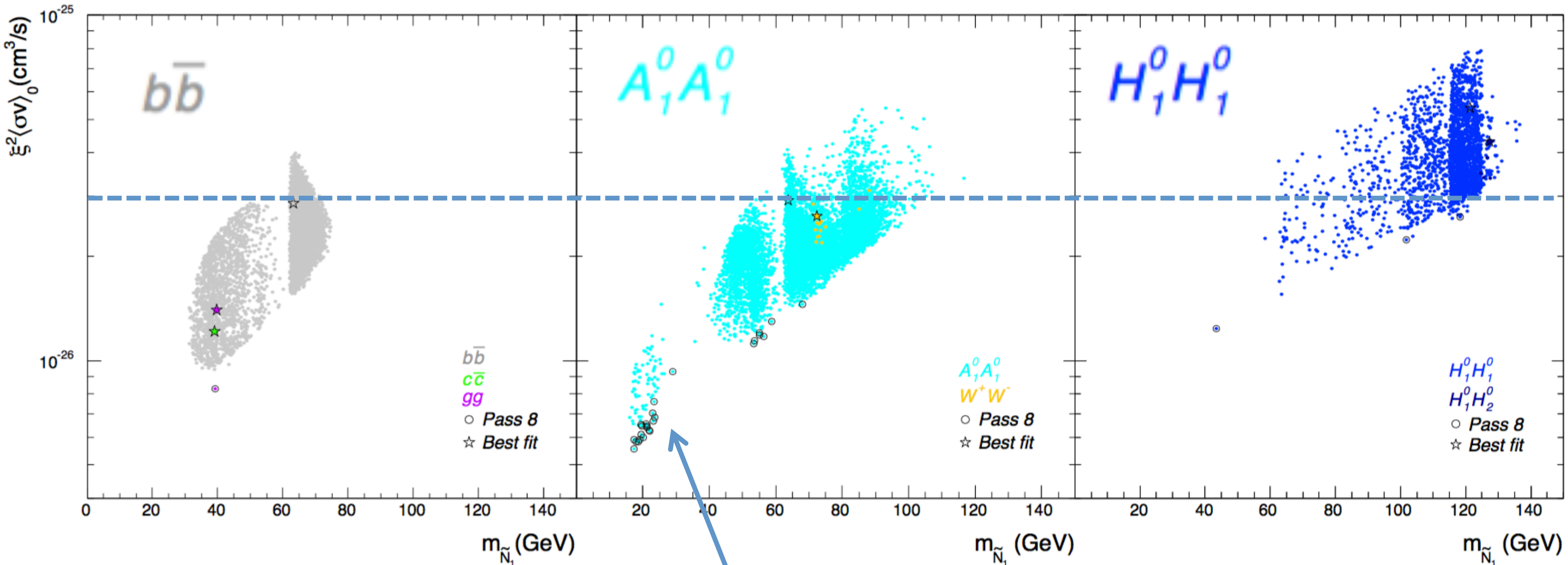
DGC, Peiró, Robles JCAP 08 (2014) 005
DGC, Peiró Robles – in progress

Excellent motivation for direct searches at low masses

Right-handed sneutrino in the NMSSM and the Galactic Centre Emission

- Perform a scan in the parameter space imposing all constraints (direct, indirect and colliders)
- The full final state is studied
  Do not restrict the analysis to pure annihilation channels.

Points fitting the GCE at 90% CL



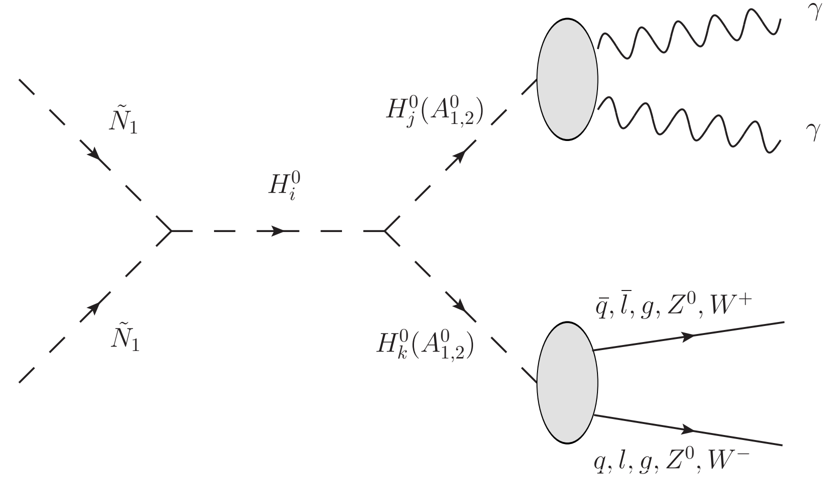
$$\tilde{N}_1\tilde{N}_1 \rightarrow 2A_1^0 \rightarrow 4\tau$$

DGC, Peiró, Robles JCAP 08 (2014) 005

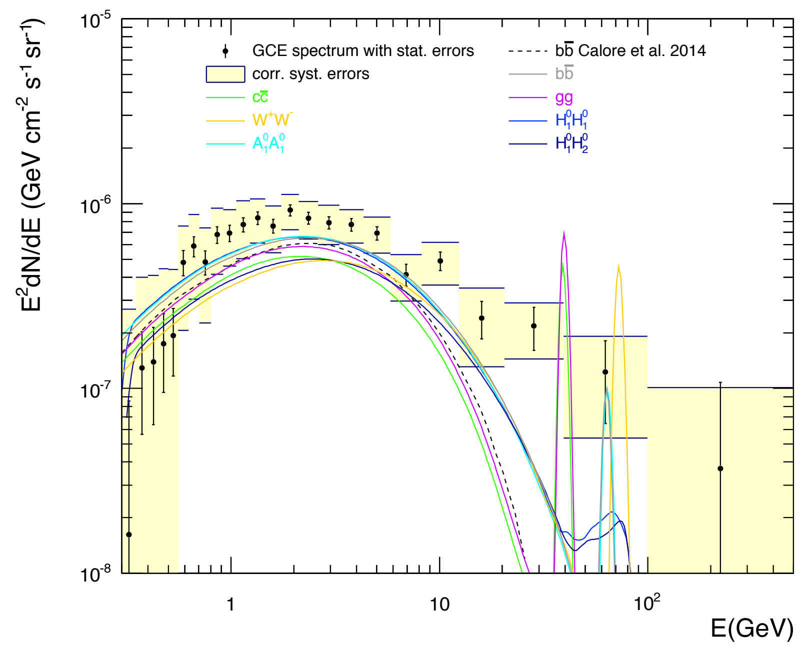
Right-handed sneutrino in the NMSSM and the Galactic Centre Emission

- Four body final states (with intermediate light scalar and pseudoscalar Higgses) are favoured

- Include spectral features (lines and boxes) that improve the fit at high energy



Final state	$m_{\tilde{N}_1}$ (GeV)	$\xi^2 \langle \sigma v \rangle_0$ (cm^3/s)	$\Omega_{\tilde{N}_1} h^2$	χ^2
$A_1^0 A_1^0$ (44.7%)	63.8	2.9×10^{-26}	0.061	20.8
$b\bar{b}$ (42.1%)	63.2	2.9×10^{-26}	0.042	21.0
$H_1^0 H_1^0$ (71.4%)	121.4	5.4×10^{-26}	0.075	21.6

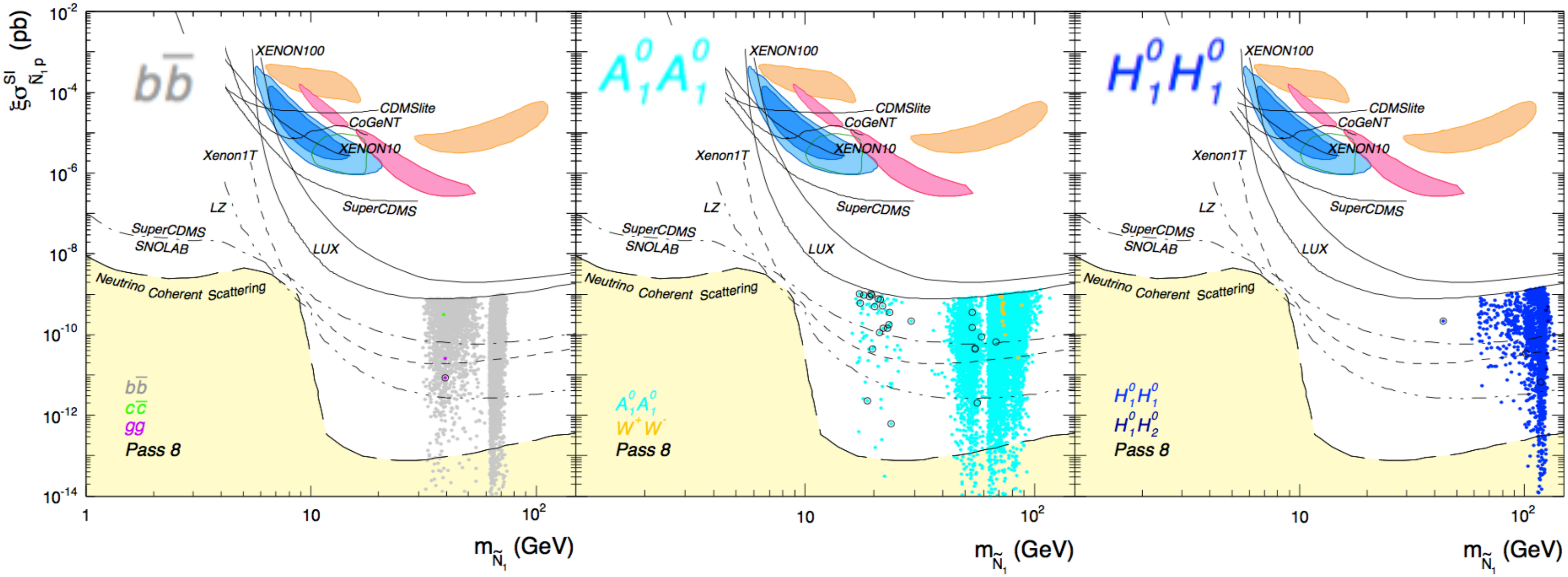


- The best fit correspond to mixed final states

DGC, Peiró, Robles JCAP 08 (2014) 005

Right-handed sneutrino in the NMSSM and the Galactic Centre Emission

- Many of these points can be checked by G2 direct detection experiments



DGC, Peiró, Robles JCAP 08 (2014) 005

Once more: Complementarity of DM searches

Taxidermy (Phenomenology-driven)

Interpret experimental results in terms of simplified models or effective Lagrangians

Identify some basic features from a positive observation

(Galactic Centre Emission)

Taxidermy (Phenomenology-driven)

Identify some basic features from a positive observation

(Galactic Centre Emission)

Perform a complementary measurement with other search technique

(Signal in various direct detection targets or at the LHC)

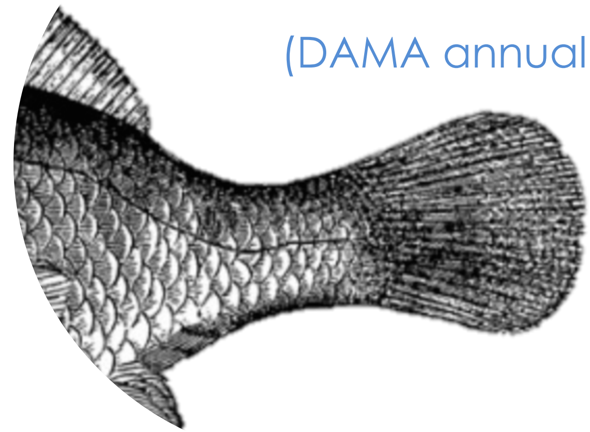
Taxidermy (Phenomenology-driven)

Identify some basic features from a positive observation

(Galactic Centre Emission)

Some data might be more difficult to explain in terms of “standard” DM models

(DAMA annual modulation)



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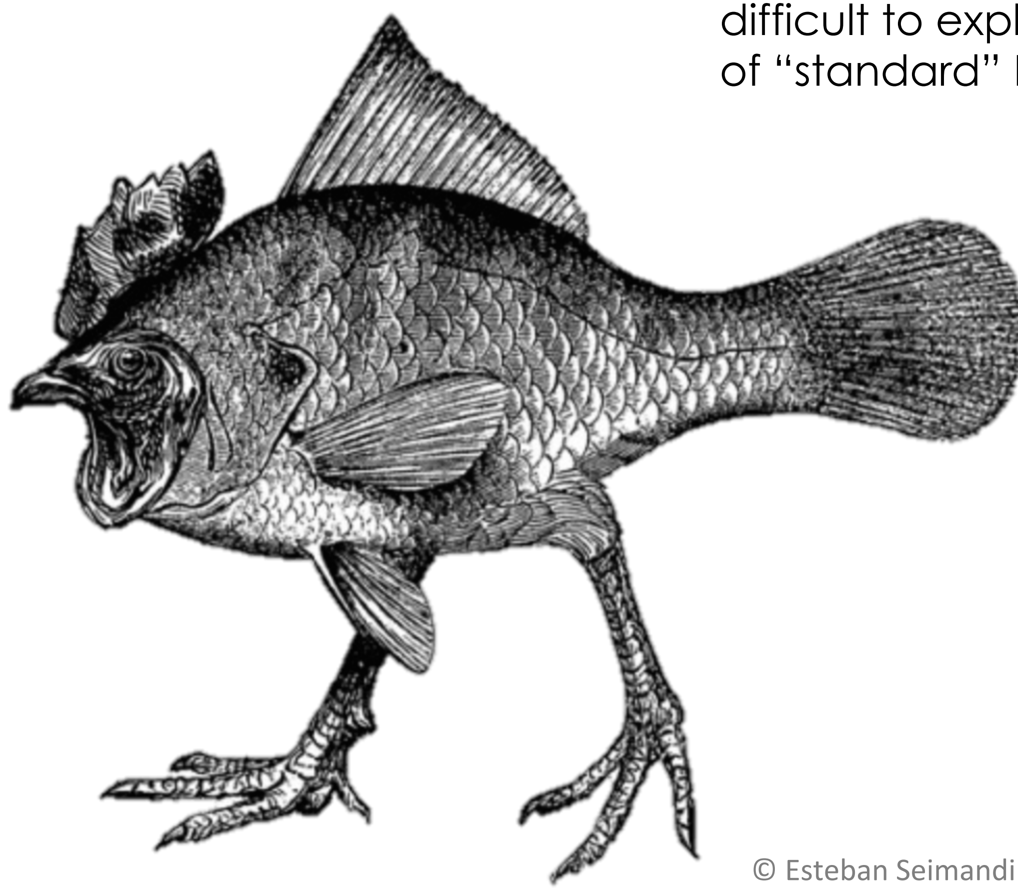


Perform a complementary measurement with other search technique

This motivates working with general frameworks, where little or nothing is assumed for the DM particle

If there is a positive detection of DM, can we identify the underlying model?

Problem:

- Experimental data allow us to reconstruct **“phenomenological parameters”**.

$$m_\chi,\ \sigma^{SI},\ \sigma^{SD},\ <\sigma v>_{ij}$$

- Theoretical models tend to produce similar results (e.g., most WIMPs are alike)

Solution:

- Data from different experiments has to be combined in order to remove degenerate solutions (and reduce the effect of uncertainties)

Design strategies that allow the identification of DM from future data

Identification of Dark Matter with direct detection experiments

Given a DM direct detection, the DM mass and couplings can be determined from the observed number of events and energy spectrum.

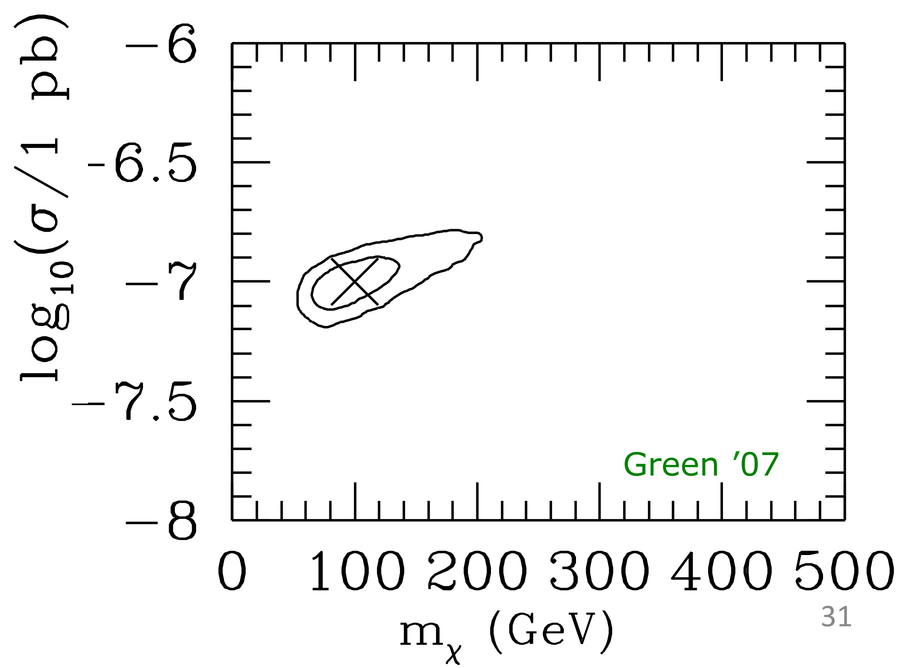
$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \boxed{\frac{d\sigma_{WN}}{dE_R}(v, E_R)}\, dv$$

$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2} \left(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right)$$

Nuclear form factors

The energy spectrum depends on the WIMP mass and the mass of the target

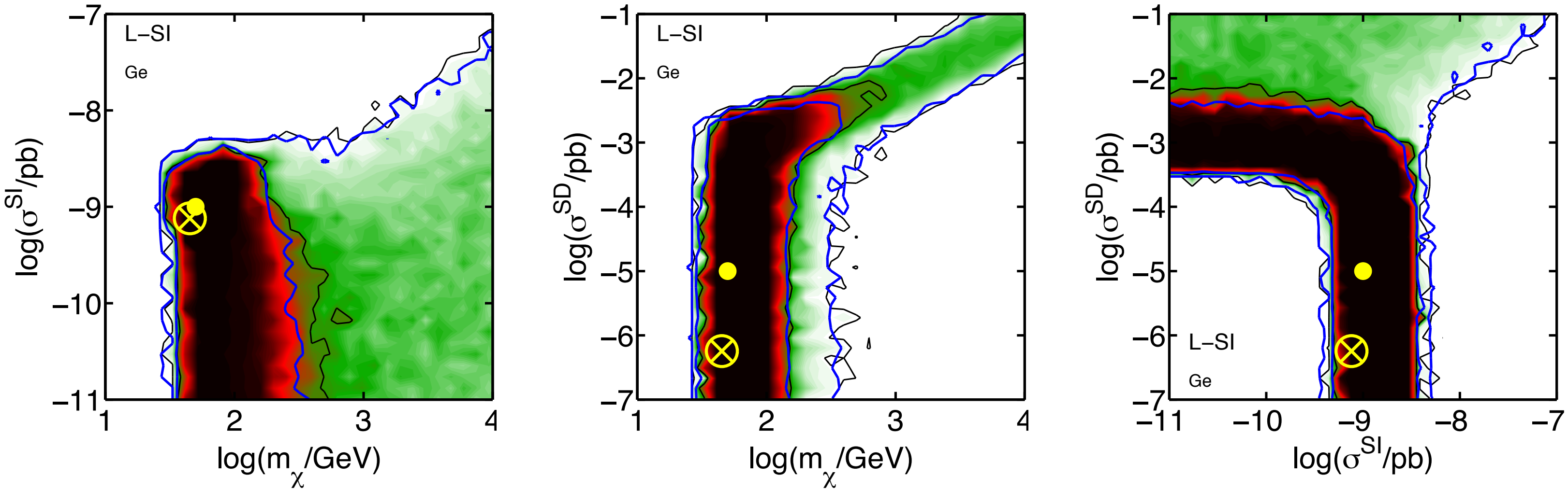
There are degenerate solutions



Example: m_χ=100 GeV
Exposure: 3000 kg day (Ge target)

We need multiple experiments (with various targets)

A single experiment cannot determine all the WIMP couplings, a combination of various targets is necessary.



$$\sigma_0^{SI} = 10^{-9}\,\mathrm{pb}$$
$$\sigma_0^{SD} = 10^{-5}\,\mathrm{pb}$$
$$m_W = 50\,\mathrm{GeV}$$
$$\epsilon = 300\,\mathrm{kg\,yr}$$

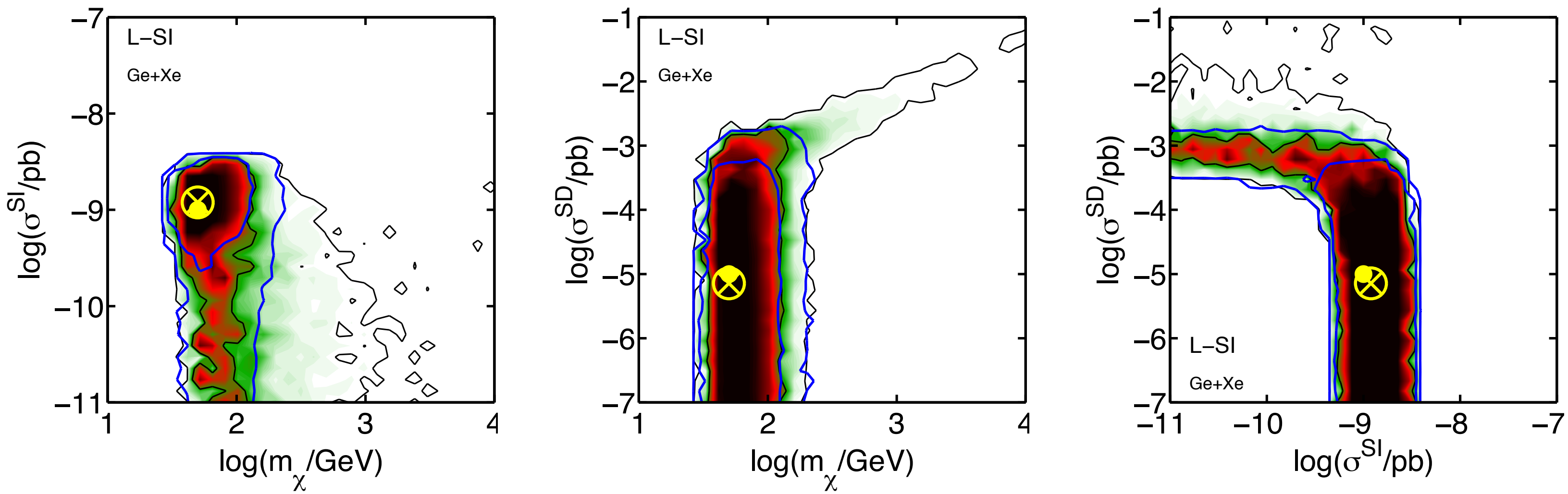
We use simulated data to assess the reconstruction of DM parameters

Astrophysical and nuclear uncertainties included

Prospects for SuperCDMS (Ge)

We need multiple experiments (with various targets)

A single experiment cannot determine all the WIMP couplings, a combination of various targets is necessary.



A combination of **Germanium and Xenon** greatly helps in reconstructing the DM parameters

Targets with different sensitivities to SI and SD cross section are needed (e.g., F, Al)

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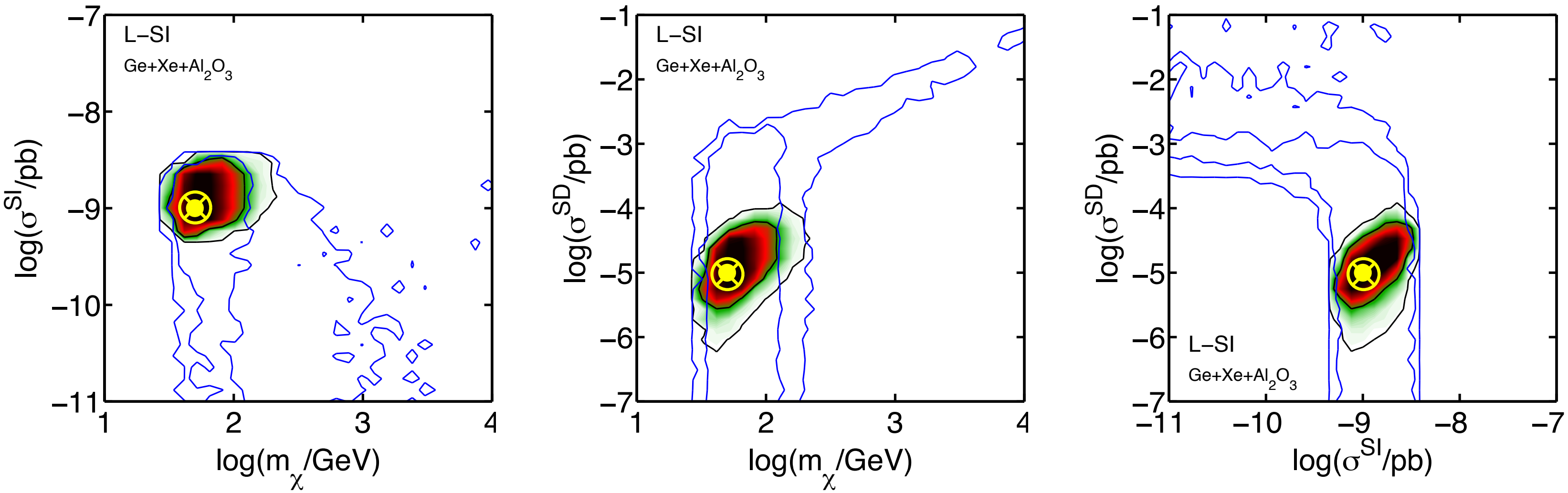


A combination of **Germanium and Xenon** greatly helps in reconstructing the DM parameters

Targets with different sensitivities to SI and SD cross section are needed (e.g., F, Al)

This is an excellent tool to help design future experiments.

Are we being too conservative in describing DM-nucleus interactions?

The most general effective Lagrangian contains up to 14 (x2) different operators that induce six types of response functions and two new interference terms

Haxton, Fitzpatrick 2012-2014

$$\mathcal{L}_{\rm int}(\vec{x}) = c\,\Psi^*_\chi(\vec{x})\mathcal{O}_\chi\Psi_\chi(\vec{x})\,\Psi^*_N(\vec{x})\mathcal{O}_N\Psi_N(\vec{x})$$

Spin-Indep.

Spin-Dep.

Angular momentum of unpaired nucleon

Angular momentum and spin

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

These operators can be obtained as the non-relativistic limit of relativistic operators (e.g., starting from UV complete models)

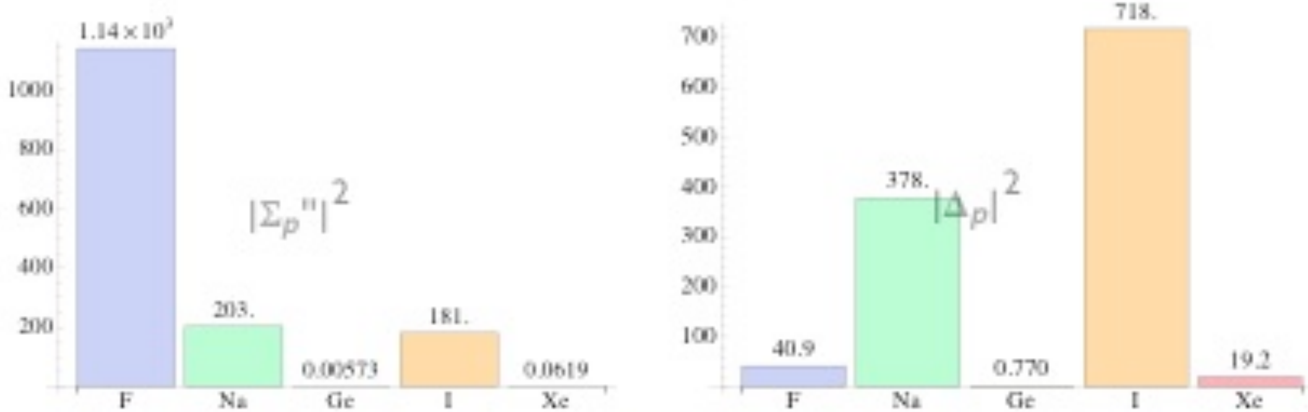
E.g., For a spin ½ particle

Scalar Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\left(\frac{h_1^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$\left(-\frac{h_1^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_6$
Vector Mediator		
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{h_3^N\lambda_3}{m_G^2}\right)\mathcal{O}_1$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(-\frac{2h_4^N\lambda_3}{m_G^2}\right)\left(-\mathcal{O}_7+\frac{m_N}{m_\chi}\mathcal{O}_9\right)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$\longrightarrow$	$\left(-\frac{2h_3^N\lambda_4}{m_G^2}\right)(\mathcal{O}_8+\mathcal{O}_9)$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$\longrightarrow$	$\left(\frac{4h_4^N\lambda_4}{m_G^2}\right)\mathcal{O}_4$

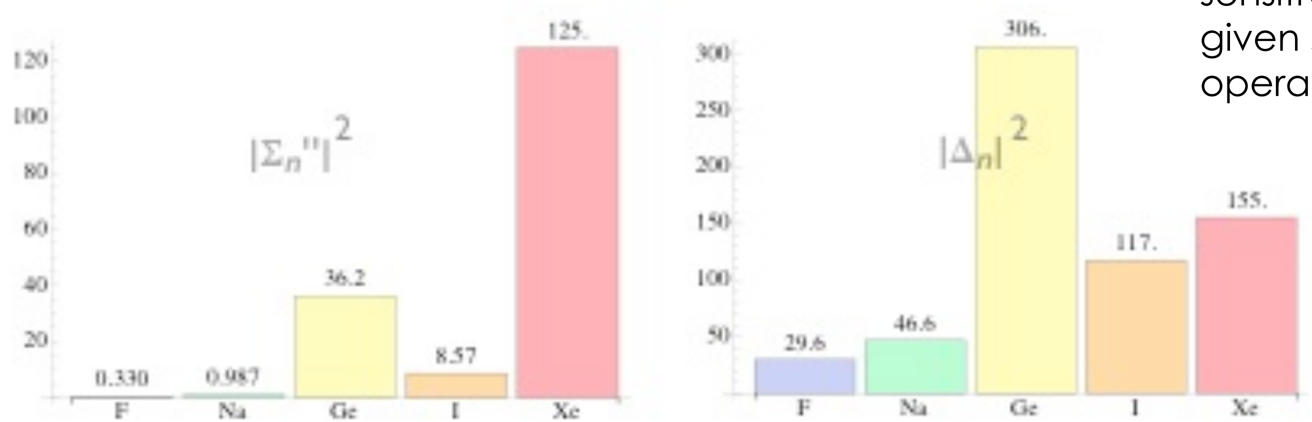
Dent, Krauss, Newstead, Sabbharwal 2015

These are extremely sensitive to the choice of target material, being crucial in the design phase of new experiments.

Vector, proton coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$



Vector, neutron coupled: $\vec{\sigma}(i)$ vs. $\vec{\ell}(i)$

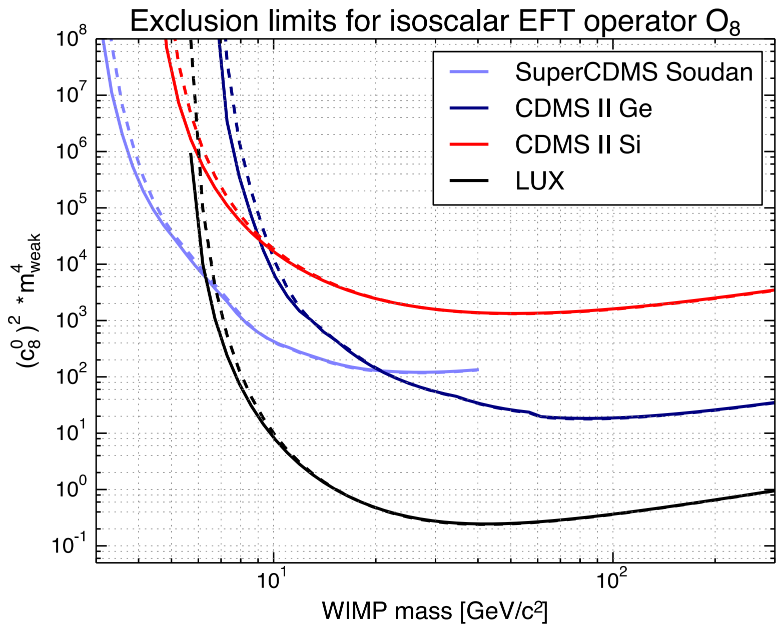


Some targets have enhanced sensitivities for a given set of operators

Limits on EFT operators (SuperCDMS)

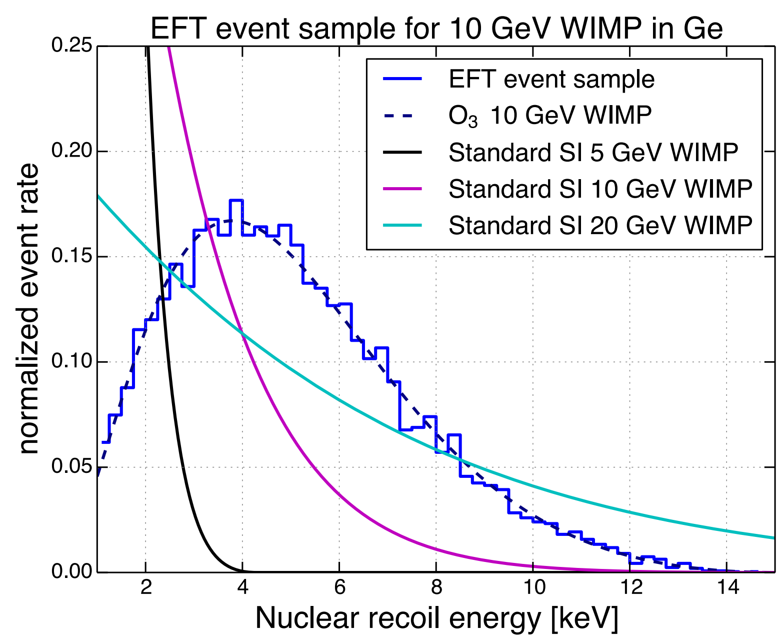
K. Schneck et al. PRD 2015

- Assume contribution from only one operator at a time
- Bounds very sensitive to the actual target
- Potential cancellations between some operators



- The spectrum differs from the expected for standard interactions

- A DM signal could be misidentified as background
- The reconstruction of a signal would point towards the wrong mass and couplings



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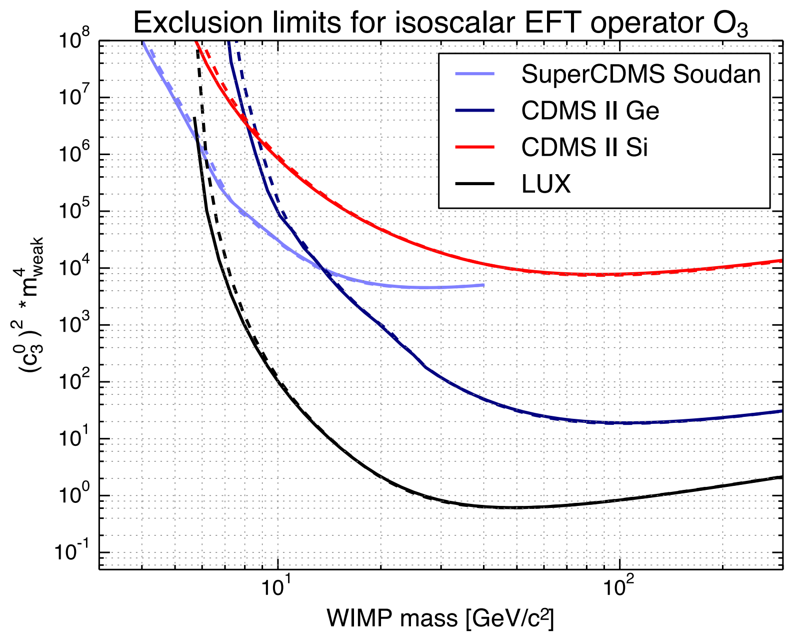

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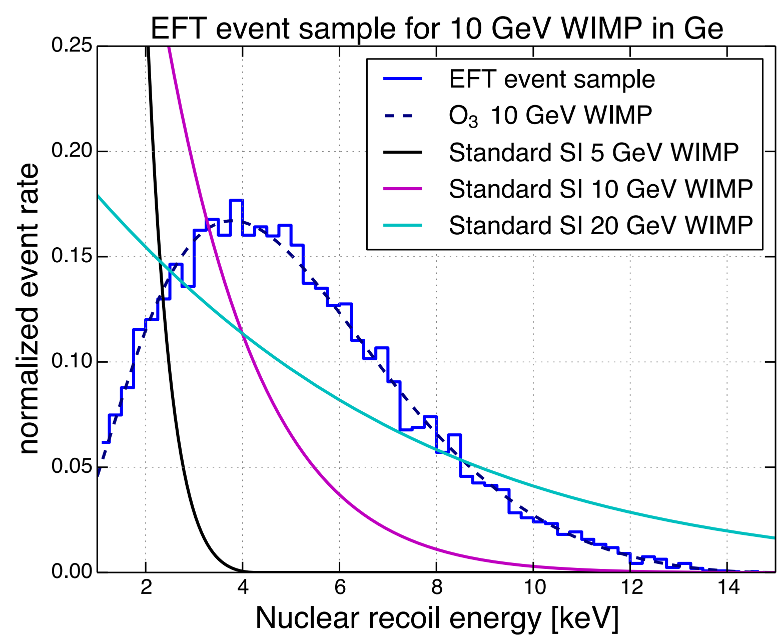

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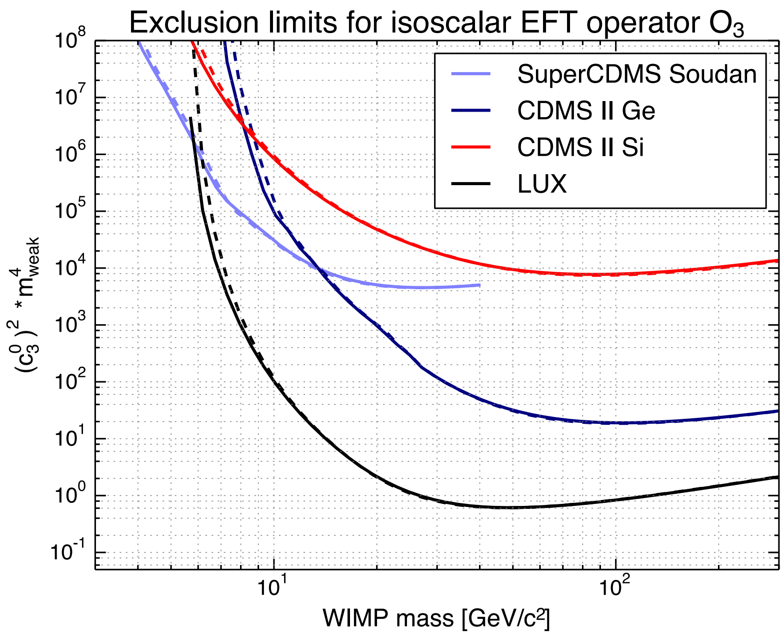

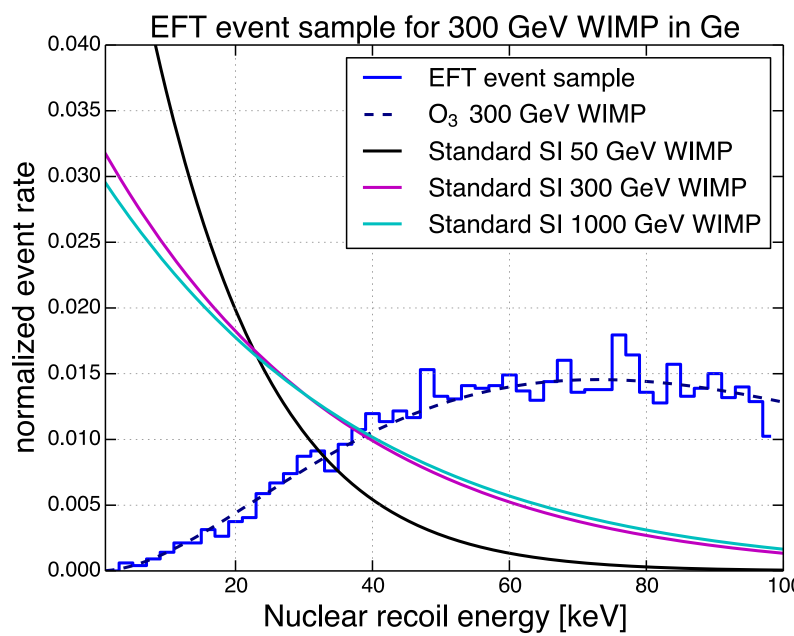

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Conclusions

Exciting times ahead with future DM experiments (direct and indirect) and the LHC

- Potential signals might be clarified (Galactic Centre Emission, DAMA…)
- New regions of the parameter space explored

Existing "well motivated" models can account for some of these observations

- E.g., Right-handed sneutrino DM and the Galactic Centre Emission

Future new data might provide information about the DM properties

- The use of multiple targets, or combination of different data is crucial
- Need to consider more general DM interactions and/or simplified models